COST-EFFECTIVE & CONTINUOUS IMPROVEMENT OF PRODUCTION PROCESS AND COMPANY’S BUSINESS WHEN USING TOTAL QUALITY MAINTENANCE (TQMain)

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ABSTRACT
A new concept of condition-based maintenance (CBM), Total Quality Maintenance (TQMain) is presented. It aims to maintain not only machines but the quality of the essential elements involved in the production process, such as methods, operational conditions, personnel competence, raw material, quality and managerial systems. The major results achieved, which are based on several case studies, are:
- Evidence of prolonging the bearing's effective live by using more accurate diagnosis is confirmed when faulty bearing installation, faulty machinery design and harsh environmental condition are considered
- Machine speed and load influence the information delivered by vibration signals
- Applying vibration spectral analysis, it is possible to detect the deviations in the quality of a product during the processing time and before it is completed
- Maintenance profit of one paper machine was found to be at minimum about 3.58 MSEK yearly

The main conclusion is; identifying and eliminating causes behind deviations in quality and equipment condition at an early stage are vital to accomplish continuous improvements and to assure longer machine live and high quality products at competitive price

KEYWORDS: Failure causes, Rolling Element Bearings, Vibration Signal Analysis, Condition and Quality control, Total Quality Maintenance, Cost-effective maintenance policy.

1. INTRODUCTION
According to a study reported by Mobley (1990), from 15 to 40% (with an average of 28%) of the total cost of finished goods can be attributed to maintenance activities in factory, Blanchard (1994). The study conducted by the Department of Trade and Industry in the UK revealed that poor and dangerous maintenance costs UK industry US$ 1.95x10^9 £ 1.3 billion a year, Rao (1993). The implementation of vibration-based maintenance (VBM) policy provides possibilities for acquiring early indications of changes of machine-state, Al-Najjar (1997). These indications could be of great importance also in detecting deviations in the product quality early and before they show on quality control charts. Cost-effectiveness is one of the criteria, which should be used to select a suitable maintenance policy. An efficient CBM policy lets the machine run until just before failure. It can be defined by two defence-lines, which are proactive maintenance (activities and efforts of detecting and correcting damage causes) and predictive maintenance (monitoring symptomatic conditions when the damage is initiated and it is under development), Al-Najjar (1996).

Real problems in production, quality and maintenance are complex, due to the interplay between many factors. Condition monitoring (CM) software programs especially for vibration became popular in many industries, such as paper and pulp mills, refineries and power stations, and recently in manufacturing industry, Al-Najjar (1997). In applications, the databases of these software programs are limited and in general not integrated with databases for operation, quality and management and accountancy. A database for a wider range of information is required for effective diagnosis and
prognosis of equipment condition, where the information required can either be found in plant's different databases or be collected.

The aim of this paper is to demonstrate the impact of using TQMain concept on diagnosis/prognosis technique, product quality and company's profits especially when the down time is expensive, such as the case in process and chemical industries. In this study, parts of TQMain are used in different case studies to reduce the difficulties that may arise when applying the whole concept. Such application demands big investment that can not be motivated without showing some results, which is impossible to highlight without successful applications. The application is performed manually to highlight the potential of using TQMain in improving data coverage and quality, diagnosis/prognosis technique, product quality and company's profits (and consequently its economic competitiveness) and to motivate companies for more investment in maintenance.

2. PRODUCTION PROCESS FROM THE PIONT VIEW OF TQMain
Trevenna and Thornycroft (1993) emphasise that in today’s business environment the challenge is to ensure equipment performance and availability whilst achieving minimum cost. Also, more attention has been focused recently on broadening the perspective of maintenance through integrating it with the production program and into a complete market-oriented system, and on the importance of utilising a feedback system in improving, e.g. productivity, quality, reliability, designs, Sherwin and Jonsson (1995). Furthermore, for any production process or enterprise to survive the harsh international competition, specific competitive advantages should be created, maintained and improved continuously. These competitive advantages are:

1. High quality production and machine
2. Competitive price
3. Delivery on time
4. Environmental friendly production process and product
5. Society acceptance

Production process capability as a measure of conformity depends on several factors, see also Fig. 1, which can be represented by the elements involved in the production process and the disturbances influence the production process. The basic elements constituting a production process may be summarised in: producing machines, tools, procedures and methods, maintenance policy, operational conditions, competence of the operating and maintenance staff, quality system, raw material and managerial functions. Deviations in the quality of any of the essential manufacturing input elements have major effect in the competitive advantage and product technical specifications (product quality). In this study the condition of the production process is defined by the state of the basic elements constituting it. In general, it is not usual that old and deteriorated equipment/processes can manufacture quality products in high effectiveness at a competitive price to be delivered on time and being environmental friendly process in the sense demanded by the society. Deterioration in equipment can be started, or developed, by means of external causes, such as misuse, bad raw material, unsuitable lubricant, inefficient maintenance, external shock and harsh operational conditions. For example, these factors constitute about 70% of the total reasons behind failures in rolling element bearings, Bloch and Geitner (1994). Therefore to prevent or reduce their effect, relevant parameters should be monitored actively.

In order to provide more accurate real-time mapping and analysis of the condition of a production process, both the product characteristics and the condition of the relevant elements involved in the production process should be monitored and assessed. This is also necessary to prolong the lead-time required for preparing and performing maintenance actions to restore the condition of a component, equipment or process to be able to function according to the specifications, Fig.1. Technical, statistical and economic analyses are effective tools to identify and assess the deviations in the condition of the production process, product quality, working environment and production costs. Vibration spectrum analysis is a powerful tool for monitoring rotating and reciprocating machines. It is also partly suitable for monitoring the working environment and personnel competence in specific areas. Vibration frequencies can be utilised to monitor the machine condition and product quality and to identify and localise a wide range of the causes behind the deviations and consequently which elements in the
production process that these causes are related to. The best output of the production process that fulfils the competitive advantages can be distinguished and achieved through selecting the suitable combination of the process elements, which cannot be achieved without using an easily accessible and special database.

**3. What is TQMain?**

One of the essential forces driving total quality management (TQM) and total productive maintenance (TPM) is the improvement cycle (Deming cycle), i.e. Plan - Do - Check - Act. Practically, this cycle has been used in a way that one should act as soon as failure is occurred. But, it can also be interpreted so that action is started at an earlier stage, i.e. as soon as a significant deviation in the equipment/process condition is observed. A study done by Bloch and Geiter (1994) reveals that about 99% of the mechanical failures are preceded by some detectable indications of condition change, see also Mann and Saxena (1995). Vibration spectral analysis, provides a basis for identification of damage causes, damage development mechanisms and failure modes for most types of faults in rotating and reciprocating machines, Collacott (1977), Bloch and Geiter (1994) and Al-Najjar (1997, 1998 and 2000). In this paper, the failure is defined as a *termination of a component’s ability, to*
perform its required function, which can be defined on basis of the machine function, capability, production rate, production cost, product quality, or personnel/machine safety.

TQMain is a means to maintain and improve continuously the technical and economic effectiveness of the production process and its elements, i.e. it is not just a tool to serve or repair failed machines rather than a means to maintain the quality of all the elements involved in the production process. Thus, TQMain’s role can be defined as: A means for monitoring and controlling deviations in a process, working conditions, product quality and production cost, and for detecting damage causes and their developing mechanisms and potential failures in order to interfere (when it is possible) to “stop” or reduce machine deterioration rate before the production process and product characteristics are intolerably affected and to perform the required action to restore the machine/process or a particular part of it to as good as new. All these should be performed at a continuously reducing cost per unit of good quality product.

TQMain promote that the data required should be gathered in a common database without the duplication that usually occurs when each department collects its own data. It also promotes the integration of the databases of relevant disciplines, which can be selected based on their significance and impact on mapping, analysis and enhancement of the production process and company’s business. Integrating data from relevant working areas has many benefits. For example, the integration of the data collected from production and vibration-based maintenance (VBM) policy provides good opportunities for monitoring, measuring and improving reliability, availability and productivity of the producing machines. Integrating the data from VBM database with those from the databases for production and quality control establishes the basis for monitoring, measuring and improving the quality rate and causes behind quality deviations in addition to the latter characteristics. The integration of the data from VBM policy and quality control provides a possibility for monitoring, measuring and improving the quality system, because VBM policy works in this context as a quality assurance tool see above. A reliable redesign and modification of manufacturing equipment can also be achieved.

When using OEE as a measure of the progress achieved by a particular improvement, there is a major question to be addressed, which is whether that progress was cost-effective? TQMain would answer whether it would be cheaper to have buffer stores to permit the required actions or to duplicate the machines as the production method might need if production had to be kept up. When the cost accountancy program is integrated with the common database, TQMain offers particular criteria and tools to assess the cost-effectiveness of the technical improvements. Establishing a common database provides the information needed for:

1. Effective diagnosis to avoid ambiguities in the condition monitoring signal, such as vibration spectra, due to changes in rpm and machine load
2. Past data can be used to assess warning and replacement levels effectively
3. Damage and failure causes can be identified and followed up with high accuracy
4. Reasons behind quality deviations can be identified and localised easily
5. Cost factors deviations can be traced effectively

Thus, the common database provides a reliable foundation for mapping, analysis and control of the deviations in the product quality, process and working conditions and production cost. Many possible optimisations and analysis are currently abandoned because people simply do not have the time to coordinate data from several sources and hunt for missing data only to find ambiguities affecting the values of model parameters.

4. FEATURES AND APPLICATIONS OF TQMain

The features characterising TQMain and distinguishing it from other maintenance techniques, such as preventive (PM), condition-based (CBM), reliability-centred (RCM) and total productive maintenance (TPM) can be summarised in the following:

1. It covers a wider range of a production process compared with the traditional maintenance concept, which deals with just machinery.
2. It is based on a new condition-based maintenance concept. It is planned and performed based on the needs arise due to the deviations in the quality of the elements involved in the production process.

3. It handles production and maintenance technical and financial problems by integrating tools and methods belong to both deterministic and probabilistic approaches.

4. It advocates the use of a common database that should be updated by real-time measurements of the essential information parameters, for real-time monitoring and assessment of the machine condition and production process technical and economic effectiveness, product quality and working environment. Thus, within TQMain, it is possible to select and improve the most informative condition monitoring system and the most cost-effective maintenance policy effectively.

5. Consequently, it provides an overall view of the condition (state) of the production process (including all the elements involved), and maintenance technical and financial impact on company’s business

6. It is based on making intensive use of the real-time data acquisition and analysis to detect at an early stage the causes behind quality and cost factors deviations and machinery malfunctions, and following damage/defect development to prolong the component mean effective life and to improve company’s profitability and competitiveness.

7. It provides tools and methods for proactive-predictive maintenance, i.e. to detect and eliminate the cause behind damage initiation. If it is not possible due to the technological limitation, detect the deviation at an early stage and predict its development to reduce (or eliminate) the risk of failure.

8. It emphasis on the systematic maintenance work combining technical, organisational and economic knowledge and experience, where all the theories, tools and methods required are, more or less, developed and verified. This systematic maintenance work starts by detecting the deviation/damage at an early stage, identifying damage initiation causes and developing mechanisms and predict the situation in the close future technically and financially.

9. It provides the basis for cost-effective continuous improvement of the whole production process and in particular vibration/condition-based maintenance policy after each renewal through confronting database history, including vibration measurements, with the replaced components, i.e. continuous cyclic improvement.

10. TQMain has been applied partly in many case studies (about ten case studies). The results of these applications have shown a big beneficial potential and possibility of applying it as a whole concept, which is now under planning together with one of the biggest companies in Sweden.

5. POTENTIAL BENEFITS OF APPLYING TQMain

The extensive use of data feedback is considered essential to accomplish cost-effective continuous improvements and to assure the achievement of the competitive advantages demanded. It would enable the user, on demand and at all levels to get reliable information for:

1. Detecting the deviations in the state of a component, machine or process, production cost, product quality and working environment at an early stage in order to control the situation when possible by “stopping” or reducing the rate of the development.

2. Selecting the most cost-effective maintenance policy and the most cost-effective condition monitoring level, such as vibration level, at which to replace components.

3. Selecting the acceptable deterioration rate to “guarantee” no sudden failure during the lead-time, i.e. the time between detecting a potential failure and action to repair it.

4. Detecting potential failures (damage under development) in machine element and follow up their development, and predicting the level of the condition monitoring parameter, such vibration level, during the close future.

5. Assessing the condition-dependent failure rate of the component during the lead-time, the probability of failure, the remaining useful working lives (residual life) of the components/equipment under consideration, and the most cost effective opportunity for performing maintenance action.
6. Identification of failure mechanisms, failure causes and failure modes with increasing diagnosis and prognosis precision by relating the past measurements to the damage subsequently found and safe lead-time achieved.

6. HOW IT IS POSSIBLE TO ACHIEVE THAT?
Total quality maintenance consists of four essential working phases (modules). In order to achieve high quality result, these modules should be applied in the same rank order shown in Fig.2. Theories, tools and methods are specially developed or adapted for the application of all these modules. The modules are for:
1. Identification
2. Description
3. Selection
4. Applications and cost-effective continuous improvement, see also Fig.2

In the first phase the major focus is to collect relevant data for mapping and analysis the production and maintenance processes to identify significant components, their failures, damage basic causes and the mechanisms for developing the damage. The output of this phase is utilised to describe the possible changes in the state of the component/equipment under consideration when the damage is initiated and is underdevelopment until failure. In other words, the deterioration process can then be described properly. Consequently, the most informative CM parameter(s) and systems that should be used for detecting these changes and follow their development can be identified effectively. CM systems are to detect deviations in the quality of the production elements at an early stage. CM technology is one of the information sources that can be utilised for mapping and analysing the condition of a component, equipment and process. But, the management work required for planning...
and performing relevant and cost-effective maintenance actions necessary for maintaining the quality of one or more of the elements involved in the production process is very important. Usually, we identify many maintenance techniques, i.e. strategies, policies, methodologies and philosophies that are technically applicable for maintaining the component, equipment in question. TQMain provides tools, methods and technical and economic criteria required to select the most cost-effective maintenance techniques and the most informative CM parameter.

Cost-effective continuous improvement cannot be approached without a reliable feedback links, such as the common database, and a reliable policy for performing continuous cost-effective improvement. Cost-effective continuous improvement means that every improvement should judged in conjunction with its cost-effectiveness and not just how technically advanced it is. TQMain provides all the tools and the methods required to perform these steps. These tools and methods are usually verified in several case studies and usually based on the common concept of TQMain. Some of these cases studies are presented below.

7. CASE STUDIES

7.1 DATA COVERAGE AND QUALITY IMPACT ON FAULT DIAGNOSIS

The study analyses vibration measurements collected during two to four years from four types of roller bearings and used by two different paper machine in two companies. The paper mill companies, A and B, have four and three paper mill machines respectively, of different ages, Al-Najjar (1998). Vibration is the main parameter used for monitoring the machines. The interval between vibration measurements varied between two and five months in A and was about three weeks in B. The paper machines, PM10 at A and PM01 at B were selected for more investigation because their databases included more replacements of identical bearings than the other machine databases. Data are formed from the measurements of ten identical replaced spherical roller bearings of type 23228ck/SKF, which are usually used at the driven side of the leading roller of drying cylinders in PM10. The bearings were selected because they belong to the most troublesome area in the machine. Also, there were not enough replaced bearings from other types to be included. In the database of the VM program at company B, three types of spherical roller bearing, which are usually used in the drying cylinders, were selected for deeper analysis due to their large number of replacements. These bearings are 23052 cck/SKF at the driven side (DnS) and 23060/ HA3C4V33/SKF, (replaced by 23060cck/C4S3V33/ SKF which has the same defect frequencies) at the driving side (DS).

98 bearings are considered in this study, i.e. 49 bearings of each type. Only 42 bearing positions are experienced replacements. The replacements are divided into five generations. 56 bearings (20 at DnS and 36 at DS) have run since their installation in August 1977, i.e. 221 months. There is only one bearing position that has experienced four replacements, two have experienced three, 16 have two replacements and the rest, i.e. 20 bearings, have one replacement during the period August ´77-January ´96. The measurements taken straight after the installation of bearings are available only for the bearings at some of the drying cylinders at both DnS and DS because they were installed during the last 3 years of the period under consideration. The vibration measurements covered the frequency range 0-300 Hz, with 400 resolution lines. The major results reported from these two case studies are identifying:

1. Analysis of data from bearings at two paper mills suggests that longer bearing lives can safely be achieved by increasing the accuracy of the vibration data
2. Indications of the possibility to prolong the bearing mean effective life by more accurate diagnosis & prognosis are confirmed when faulty bearing installation, faulty machinery design, harsh environmental condition & when bearings are replaced as soon as its vibration level exceeds the normal, Al-Najjar (1998)
3. The requirements to establish a routine for improving VBM continuously.
4. Low vibration frequency range 0-1000 Hz can be used to detect faults at an early stage. The study results were discussed with the maintenance staff to establish changes in the measurement, analysis, diagnosis and replacement policies.
7.2 IMPACT OF THE OPERATIONAL CONDITION ON THE DIAGNOSIS OF VIBRATION SPECTRA

The paper mill company under study has several paper mill machines of different ages. One paper machine, called PM1, was selected for investigation because its database included more replacements of identical bearings than the other machines’ databases. Data from production and maintenance departments during two months were used in this study. The vibration was the main parameter was used for monitoring the machine’s condition. Vibration measurements of ten identical replaced spherical roller bearings of type 23228ck/SKF which are usually used at the driven side of the leading roller of drying cylinders in PM1 formed part of the data.

According to the personnel experience, the most troublesome area in the machine was the drying cylinder group. The vibration measurements at these ten bearing, which were unfortunately few, are done in three directions vertical, horizontal and axial. Only the measurements in the axial direction are analysed because they represented bearing’s condition much better than the measurements in the other directions. This is due to the high stiffness in the axial direction and that these spectra were more informative. The vibration measurements made at these roller bearings covering the period under study (from 940901 to 941231). The measurements were done only one time a day in specific days. Records of machine operating conditions, which were usually registered two to three times/day and were reported manually from production department in formal tables, were also gathered for the same period.

The data which are formally considered in these reports were: machine operating speed and load in specific parts of PM1, such as press and drying cylinder groups, number of stoppages and their times, reasons behind stoppages and the machine part where the failure happened, (if they were known). In order to distinguish the changes in vibration spectra, only the bearings, which acquired two or more vibration measurements during the study period, are considered significant. The 3rd and 4th drying cylinder groups in the paper machine PM1 were considered for more analysis because they were identified by the company as significant parts of the problem area. The vibration measurements were done at the bearing houses of the driven side (DS) of two groups of lead rollers (LR) that lie in the 3rd and 4th drying cylinder groups, respectively. Due to lack of measurements only some of the ten bearings at DS of these LRfs could be considered in the analysis. The following data were gathered: machine speeds (X), amplitudes of the 1st, 2nd and 3rd multiple of (X) and amplitudes of the frequencies at the range 15*X - 36*X. The frequencies in this range are, in general, correlated to the changes in the bearing condition (Al-Najjar 1997), vibration levels, such as overall RMS, synchronic RMS, sub-synchronous RMS, non-synchronous RMS and the load at the 3rd and 4th drying cylinder groups. The major results achieved are:

1. Identification of and ranking the areas of major problems.
2. The result of the data analysis reveals appreciable changes in the amplitudes of the specified vibration frequencies when operating conditions were changed.

7.3 VIBRATION SPECTRAL ANALYSIS AS AN QUALITY ASSURANCE TOOL

It is an attempt to test the possibility of using integrated VBM (on the basis of TQMain concept) as a quality assurance tool in addition to its role in detecting changes in machine condition especially when a vibration monitoring system is already implemented at the company. At Volvo Division Motor, Skövde, Sweden, crankshafts are polished at the end of the production line by special lapping bands of grain size 90 and 30 μm in two consequent stations. Main bearings of the 5-cylinders crankshaft (type 590) acquire faulty profiles, such as conic, concave or convex instead of the cylindrical. It was not clear where in the process this deformation in the cylindrical form of the main bearings is started and developed, and if these deviations exceeded the maximum allowable tolerance, which is 8 μm, or not. This tolerance represents the maximum difference between three measurements done at three points along each main bearing. The company’s goal is to keep the maximum difference (at one side measurement) equal to or less than 2 μm.
Crankshafts’ are washed before the final control at the measuring machine is made. Due to the use of environment-friendly washing soap at the washing machine appreciable amount of dirt (bacteria) often accumulates at the main bearing surface. Many of the crankshafts, which were rejected, were suspected to be of good quality, but covered by a layer of dirt that confuses the measuring system. Lapping, washing or/and measuring machine is suspected to cause the deviation in the main bearing profile. An experiment was conducted on about 750 crankshafts to distinguish the reasons behind rejecting crankshafts and to collect data for statistical analysis to highlight the proportion of crankshafts that acquired faulty profile, which main bearing was most exposed to faulty profile and which profile was the most usual. The main results of the previous arrangement were; firstly, all the tested crankshafts but two, which acquired maximum difference values greater than 10 μm, were accepted after the new measurement. This means that measuring machine was working satisfactorily and the error in the measurements was actually due to the accumulated dirt generated at the washing machine. The second important result was; the main bearing number three was identified as the most troublesome part of the crankshaft. Further, the most usual faulty profile created during manufacturing was concave. This is why we focused in this study on one faulty profile (concave) and main bearing number three of the 5-cylinders crankshaft of type 590. Ishikawa diagram was used to analyse the lapping machine technically, which was responsible of this quality problem i.e. to identify cause-result relations. The analysis resulted in identifying the basic reasons behind initiation and development of concave profile at main bearing number three. They are:

- Deterioration in the joints of the lapping-band shoe arms increased the clearance and consequently the deviation in the shoe positioning
- Faulty installation of the lapping-band shoe/shoe holder and lapping band
- Existence of dirt in (and around) all the joints.

Real two levels factorial experiment was conducted and the factors considered in this experiment were condition of the lapping-band shoe, condition of the lapping band (deformed longitudinally or not) and existence of dirt at (and around) the lapping-band shoe and shoe holder. These three factors were examined in eight combinations, randomly conducted and five crankshafts were produced at each. At the same time vibration measurements were picked up simultaneously from six accelerometers, which were mounted at the suspected reasons sources. Machine spindle speed was measured continuously. We focused only on station number two of lapping machine because about 15-20 μm of a crankshaft are removed while about 5 μm are removed at station three.

Data analysis gave the results:
1. Levels of vibration frequencies were varying, low but distinguishable in all vibration spectra and measuring directions.
2. Using vibration spectra, it was possible to detect deviations in the main bearing surface quality, see Al-Najjar (2001).
3. Statistical analysis of quality data revealed that cleanness of the lapping process has the biggest negative effect on the crankshaft’s quality and condition of the lapping-band shoe was less probable effecting crankshaft quality while rest of the combinations are of negligible effect.

7.4 ECONOMIC IMPACT ON COMPANY’S PROFITS WHEN USING VBM

The case study was conducted at StoraEnso (a paper mill company in Hyltebruk area in the southern part of Sweden). The data collected was delimited to only stoppages of mechanical components, which were (or could be) monitored by vibration signals. The study was conducted at PM2, one of the company’s four machines. It was selected due to its valuable database especially during study period (1997-2000). A special data sheet was designed for collecting manually technical and economic information parameters from the company databases. The data sheet was adapted to suit the company terminology and context. Technical data included parameters, such as operating time, production rate, time and frequency of stoppages in which mechanical tasks, e.g. bearing replacements, were performed as a result of using VBM, failures, short stoppages, quantity of bad quality products caused by maintenance problems. Economic data such as fixed and variable operating costs, profit margin, net profit, working capital, direct maintenance costs, investments in maintenance, spare parts inventory, etc. were also collected. Direct maintenance cost, which was almost constant during the study period with an average of about 13 MSEK. Total maintenance investment in PM2 was increasing for the
years 1997-1999 with a little bit decrease in year 2000, on average it was about 0.455 MSEK per year. Total production losses (potential savings or maintenance potential income) consists of the summation of lost profit and unutilised costs calculated for unavailability due to unplanned and planned stoppage times, short stoppages, bad quality products caused by maintenance problems, and tied up capital due to extra spare parts. On average the total potential saving was about 30 MSEK, and it was increasing for the total losses elements. Losses due to short stoppages represent the highest value, then the planned stoppages, and quality problems, after that come the failures, finally the tied capital due to extra spare parts inventory, which was calculated with respect to year 1997. On average the minimum savings was estimated to be about 4 MSEK, which was increasing especially during the years 1999 and 2000. The last factor is maintenance profit, which represents the difference between the minimum savings and maintenance investments. On average it was about 3.58 MSEK.

Twelve maintenance-performance measures were developed and used. The first and second performance measures are the direct maintenance cost (mechanical), and total investments in maintenance. The third, fourth and fifth are the ratio of the direct mechanical maintenance costs to operation cost, running time and accepted product, which showed approximately the same trend (almost constant) during 1997-2000. The sixth measure is the total losses (in profit and resources) per each accepted ton produced. It shows that on average about 168 SEK were lost for each ton of paper produced, and, also, the trend of losses is increasing. The seventh measure is the minimum savings divided by the accepted tons of paper produced. The eighth measure is the ratio of maintenance investments to potential savings. It was appreciably small and varied between 1-2.2%. The ninth measure is the ratio of minimum savings to maintenance investments on average it was about 9.2 which was high and within the range achieved internationally, i.e. 5-10. The tenth measure is the ratio of lost profit to actual profit. We noticed that on average a value of about 3.5% of the actual generated profit could have been gained for lost production during failures and short stoppages. Note that the quantities that are not produced during the planned stoppage time are not included. The eleventh measure is the restricted overall process effectiveness (ROPE). ROPE is equivalent to OEE but restricted to only when the machine is subjected to mechanical faults that can be maintained by VBM. Finally, the last measure, which represents the value of ROPE, divided by the direct mechanical maintenance costs, Al-Najjar and Alsyouf (2004).

CONCLUSIONS
In general, using TQMain would enable the user, on demand and at all levels from the executive manager to the operator, to get reliable information about:
1. The deviations in the process to control the situation at an early stage.
2. Cost-effective vibration-level to replace components suffering deterioration.
3. Acceptable deterioration rate to avoid sudden failure during the lead-time.
4. Potential failures and prediction of remaining useful working life.
5. Probability of failure during the lead-time.
6. Failure mechanisms, causes & modes to ease and enhance their identification tools.
7. Cost-effectiveness of using the CM system.

The implementation of TQMain can be carried out easily if the integration is achieved gradually and expanded after each successful extension. Better (and relevant) data coverage and quality, which is
easily accessible, increase the possibility of achieving Just in Time Maintenance concept. This together with vibration measurements help to detect damage initiation and following its development, effective diagnosis and prognosis, effective control of the condition of machinery and less production losses. The variation in the machine load and speeds influences the amplitudes of rolling element bearing defect frequencies and such changes should be considered when interpreting vibration spectra. This will improve the effectiveness and accuracy of fault diagnosis and prediction of the time to maintenance action. Using TQMain concept, makes it possible to detect causes and their development mechanisms that are behind deviation in the machine condition and product quality at an early stage. The quality and reliability of product and equipment, respectively, will then be maintained and a higher overall equipment effectiveness at a low cost can be approached consequently. Vibration spectral analysis can be used as a tool for quality assurance, which enables the user to detect quality deviations at an earlier stage than when using traditional quality control diagrams in order to eliminate the causes and prevent the machine from manufacturing defective items. The quality problem causes that were identified technically were confirmed by both vibration signal analysis and quality data analysis. Using the suggested LCC model means that cost factors will be used as monitoring parameters to provide the required information for decision-making and to insure cost-effective actions and enhances never ending improvement efforts. Comparing the minimum savings with the investments done for improving maintenance policy reveals how cost effective the investment in maintenance was and whether it was relevant or not.

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